

## SOLAR CYCLE #24 AND THE SOLAR DYNAMO

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### ABSTRACT

We focus on two solar aspects related to flight dynamics. These are the solar dynamo and long-term solar activity predictions. The nature of the solar dynamo is central to solar activity predictions, and these predictions are important for orbital planning of satellites in low earth orbit (LEO). The reason is that the solar ultraviolet (UV) and extreme ultraviolet (EUV) spectral irradiances inflate the upper atmospheric layers of the Earth, forming the thermosphere and exosphere through which these satellites orbit. Concerning the dynamo, we discuss some recent novel approaches towards its understanding. For solar predictions we concentrate on a “solar precursor method,” in which the Sun’s polar field plays a major role in forecasting the next cycle’s activity based upon the Babcock-Leighton dynamo. With a current low value for the Sun’s polar field, this method predicts that solar cycle #24 will be one of the lowest in recent times, with smoothed F10.7 radio flux values peaking near  $130 \pm 30$  ( $2 \sigma$ ), in the 2013 timeframe. One may have to consider solar activity as far back as the early 20<sup>th</sup> century to find a cycle of comparable magnitude. Concomitant effects of low solar activity upon satellites in LEO will need to be considered, such as enhancements in orbital debris. Support for our prediction of a low solar cycle #24 is borne out by the lack of new cycle sunspots at least through the first half of 2007. Usually at the present epoch in the solar cycle ( $\sim 7+$  years after the last solar maximum), for a normal size following cycle, new cycle sunspots would be seen. The lack of their appearance at this time is only consistent with a low cycle #24. Polar field observations of a weak magnitude are consistent with unusual structures seen in the Sun’s corona. Polar coronal holes are the hallmarks of the Sun’s open field structures. At present, it appears that the polar coronal holes are relatively weak, and there have been many equatorial coronal holes. This appears consistent with a weakening polar field, but coronal hole data must be scrutinized carefully as observing techniques have changed. We also discuss new solar dynamo ideas, and the SODA (Solar Dynamo Amplitude) index, which provides the user with the ability to track the Sun’s hidden, dynamo magnetic fields throughout the various stages of the Sun’s cycle. Our solar dynamo ideas are a modernization and rejuvenation of the Babcock-Leighton original idea of a shallow solar dynamo, using modern observations that appear to support their shallow dynamo viewpoint. We are in awe of being able to see an object the size of the Sun undergoing as dramatic a change as our model provides in a few short years. The Sun, however, has undergone changes as rapid as this before! The weather on the Sun is at least as fickle as the weather on the Earth.

### INTRODUCTION

This paper will concentrate on solar prediction requirements of flight dynamics. Namely, these are the solar dynamo and long-term solar activity predictions. The reason both are included is that the solar dynamo drives solar activity and future activity levels are an important component in orbital decay of satellites in low Earth orbit (LEO). Changes in the short wavelength irradiance of the Sun affect the upper atmospheric density and the drag on satellites

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<sup>\*</sup> Work performed under NASA MOMS Contract (NNG04DA01C)

in LEO; these changes strongly impact the orbital paths and lifetimes of satellites in LEO. The particular predictions are related to our understanding of the solar dynamo. Our ability to predict the Sun's dynamo is further dependent upon a methodology formulated several decades ago and dynamo theories previously developed by Babcock and Leighton in the 1960's. This paper's sections are: an historical perspective, the solar dynamo, a prediction for solar cycle #24, observations related to the Sun's polar magnetic field, the dynamo as a shallow percolation process, and summary and conclusions.

## HISTORICAL PERSPECTIVE

The short wavelength solar irradiance is greatly affected by the Sun's activity, varying by a few percent in the ultraviolet (UV) to more than 100% at some wavelengths in the extreme ultraviolet (EUV) over a solar cycle. Therefore, predicting the solar irradiance requires a prediction of solar activity. Although sunspot number,  $R_z$ , is generally used by solar physicists as an index of solar activity because of its long record of use, space scientists, particularly the orbit determination community, have more commonly used the spectral irradiance at a wavelength of 10.7 nm (F10.7) as a general and accessible measure of the Sun's activity. Radiation at this wavelength provides a more linear index to the strength of the short wavelength variations occurring in the solar corona (the UV and, more importantly, the EUV), which affect the Earth's thermosphere and exosphere. Sunspot number is a photospheric feature, with the photosphere being the source of the Sun's visible radiation, and hence, is a better index for the varying output of sunlight. However, the visible variations are only ~0.2%, whereas the shorter wavelengths vary from a percent to 100s of percent throughout the solar cycle.

Methods for solar activity forecasting were outlined in a report of a NOAA panel convened to forecast the strength of Solar Cycle 23 (ref. 1) and updated more recently for Solar Cycle 24 (ref. 2). Many of them are numerical, that is, based upon various methods simply because a mathematical method exists to perform the calculations. The best example of such a numerical or numerical scheme that had been used extensively in the past but is not practiced today is Fourier analysis of the sunspot time series. We all know how to do this, and therefore the method is so enticing that we are immediately drawn to it, secure in the knowledge that "we know what we are doing." What we really know is not why Fourier analysis should work, but rather the details of the mathematical procedure we are using. Fourier developed these ideas about 200 years ago, and it has been shown that any sufficiently well-behaved time series can be represented by a set of Fourier coefficients. For the purpose intended, i.e., of obtaining a complete set of orthonormal functions that allow a reasonable function to be described, Fourier analysis works fine. The method has sufficient degrees of freedom to represent any index we dare predict, however, we now know that these methods cannot be used for chaotic systems. The reason is that for a chaotic system, there is often more information beyond the index that one is trying to predict, and that recent past data is more significant than older data, as chaotic systems lose information with time. Thus the extendibility of predicting into the future is increasingly limited unless new data is forthcoming. As weather forecasters have discovered, our window into the future is limited by the nature of the chaotic system. Fourier analysis, however, has its coefficients determined equally by data at the beginning of the data set, as by data at its end, so it treats all data equally without regard to its temporal relevance. Because of the chaos inherent in atmospheric dynamics, weather forecasters do not use Fourier analyses to determine the temperature of various cities, because there is no physical or causal link between Fourier analysis and the temperature at a location. Thus the physics is more important than the numerical scheme. So too, the use of many, many methods of predicting solar activity have no physical basis, but exist only because they are attractive to a particular user.

Thus we focus our discussion of prediction techniques on our solar "precursor" method. We use the term precursor to mean a parameter that has variations correlated with and preceding the solar activity that we are attempting to predict. For this parameter, we should settle only for a physical quantity that may plausibly be causally connected to solar activity. The original precursors were geomagnetic; these were found by the Ohls (ref. 3). The correlations found by the Ohls were very high, but there was no known physical connection or causal agent for their findings. The difference between a correlation between parameters and a causal agent (which has been called a precursor in this field of study) may be understood by considering the following scenario. A cock crows at sunrise every morning. There is a correlation; the cock crows before each sunrise, but the cock presumably does not cause the Sun to rise. The physical cause, or causality, is not associated with the cock's behavior and the subsequent sunrise. In a private discussion with Ohl<sup>†</sup>, he said he did not consider that there might be a solar connection as a

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<sup>†</sup> Ohl, A. I., private communication, 1990.

physical cause for his findings. It was a mystery how the Sun could broadcast knowledge of its future activity level. Yet the correlations were extremely high (>95%). We found a solution involving a physical parameter, the strength of the Sun's polar magnetic field, which could affect both the geomagnetic storms the Ohls were seeing and future solar activity (ref. 3). Thus we were able to turn a surprisingly high correlation between the Earth's geomagnetic fluctuations with future solar activity, which appeared not to have any obvious causal relationship into a useful forecasting tool using solar precursors. The lack of a causal relationship was troubling, as there did not seem to be a way that geomagnetic activity could affect the Sun's dynamo. Nevertheless, turning Ohls' findings into a useful forecasting tool would likely not have been possible had the clue that the Ohls provided not been present, nor had the dynamo views of Babcock and Leighton not been developed. Essentially, a jigsaw puzzle was laid down before us, and we simply assembled the precut pieces.

We began by using the polar fields of the Sun to predict solar activity based upon the dynamo views, wherein the polar field is magnified by dynamo effects (ref. 4). This method has a physical basis rather than a purely numerical basis. The term "precursor" has been applied to geomagnetic and solar prediction techniques using signals that precede solar activity, much as in terrestrial meteorology, where low atmospheric pressure often precedes rain. The solar dynamo method was first tested with 8 prior solar cycles before being published in 1978. This method has a physical basis rather than only the numerical basis that most other schemes involve. With regard to the geomagnetic and solar precursor methods, the basis is the solar dynamo theory, which we will discuss in the next section. Let us mention here, however, we use the most respected solar dynamo understanding of the Sun's fields: the Babcock (ref. 5)-Leighton (ref. 6) dynamo models. In their models, although it was not recognized as a possible predictive technique, the polar field at solar minimum serves as a "seed" for the toroidal field that erupts into the next cycle's activity. Further support for the polar field precursor model comes from a recent modeling effort by Wang, Lean, and Sheeley (ref. 7), where it was found that the initial polar field correlated with solar cycle amplitude for cycles -3 through 22 using a flux transport model.

We shall be using the terms "poloidal" to describe the North-South, or meridional component of the solar magnetic field and "toroidal" for the East-West, or longitudinal component of the Sun's magnetism. The North-South fields of the Sun are sometimes described as "polar" and sometimes as "poloidal." The polar field describes only the poloidal magnetic field that emanates out the poles of the Sun. These are limited to very high latitudes (>60 degrees), whereas the poloidal field describes any magnetism that has a N-S component. Since much of the poloidal field often translates into subsequent polar field, we often examine all sources of poloidal field, although they have not yet reached the polar latitudes. The East-West fields are often described by solar dynamo theorists as toroidal, as generic description of fields that are primarily longitudinal. Sunspot fields are primarily toroidal, but they have a key poloidal component too, owing to the tilt of active regions. This tilt is an important aspect of dynamo evolution, as it is through this tilt that the toroidal component transforms into poloidal components. In any case, we shall be using the two terms: poloidal and toroidal generically to refer to the orientation of the Sun's magnetism as meridional vs. longitudinal.

We can understand how the methods work, as follows. Using a combination of poloidal and toroidal fields, Schatten and Pesnell (ref. 8) create a SODA (Solar Dynamo Amplitude) index as an estimate of the amount of buried solar magnetic flux. Often in their studies, proxies have been used for these components, when they were more readily available for the direct field observations. To understand the basic nature of their equation, let us examine the case of low toroidal field. Their equation then simplifies to:

$$F10.7 \sim 60 + 1.14 B_p, \quad (1)$$

where F10.7 is the predicted future peak of solar radio flux, and  $B_p$  is the current polar field in units of  $10^{-2}$  Gauss. The polar field is used here, rather than the poloidal field, as in the Babcock-Leighton theory it is the polar field at solar minimum which is regenerated into future toroidal field and hence solar activity. Thus, for a current value near 0.5 Gauss, the equation yields a prediction of 117 for peak F10.7. The stronger the polar field, the larger the level of future solar activity predicted. A more recent update to the equation shows a slightly higher second constant of about 1.2. Recently, the prediction has been updated to a value of  $130 \pm 30$  ( $2\sigma$ ) for peak smoothed F10.7. Below, we discuss the Sun's polar field precursor method with recent field data, as well as some modern developments of solar dynamo theory that can augment the Babcock-Leighton picture.

Since 1978, our methods have predicted three solar cycles quite well. Figure 1 shows F10.7 radio flux data, in units of  $10^{-22} \text{ J s}^{-1} \text{ m}^{-2} \text{ Hz}^{-1}$ , over the past 50 years, along with the past three predictions. Cycle #23 extends from 1996 through approximately 2007, with cycle #24 starting thereafter. Examining Figure 1, one notes that the timing of earlier cycles was off by roughly one year. We have been improving the timing methods. Nevertheless, the stochastic nature of solar activity results in some variations that are not readily eliminated in advance. The amplitude predictions, however, have an excellent track record.

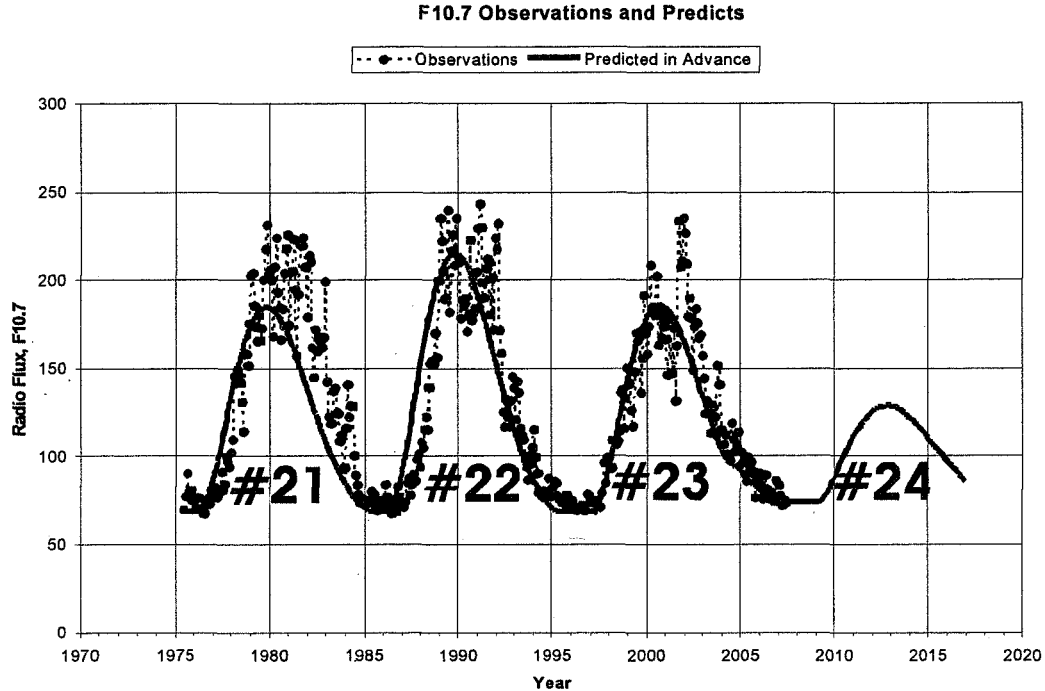


Figure 1. Observed F10.7 Radio Flux (circles) and Schatten et al. Solar Flux Predictions (solid lines) prior to each of the last three cycles. Radio Flux is in  $10^{-22} \text{ J s}^{-1} \text{ m}^{-2} \text{ Hz}^{-1}$ . Cycle #21 peaked ~1980; cycle #22 ~1990; cycle #23 ~2000; and cycle #24 is predicted to peak ~2013.

## THE SOLAR DYNAMO

Let us briefly review some key aspects of the Sun's dynamo that relate to our prediction method. Babcock described the magnetic dynamo as a basic oscillation of the Sun, wherein the polar fields of the Sun are wrapped up by differential rotation in the shallow layers of the Sun, and then erupt to form sunspots or active regions. The preceding and following sunspot groups are distinguished by the letters p and f, and this distinction is shown in Figure 2 from Babcock's drawings. The preceding and following fluxes are noted particularly in these kinds of drawings, as they relate to the discovery by Hale et al. (ref. 9) of the manner in which they relate to the polar fields. This allows us to distinguish "old cycle sunspots" from "new cycle sunspots," and this is a key as to how the dynamo is progressing in time. Thus, at present (mid 2007) we are seeing only old cycle sunspots, which leads us to believe that cycle #24 will be late and quite probably smaller than recent cycles.

# Babcock's dynamo view

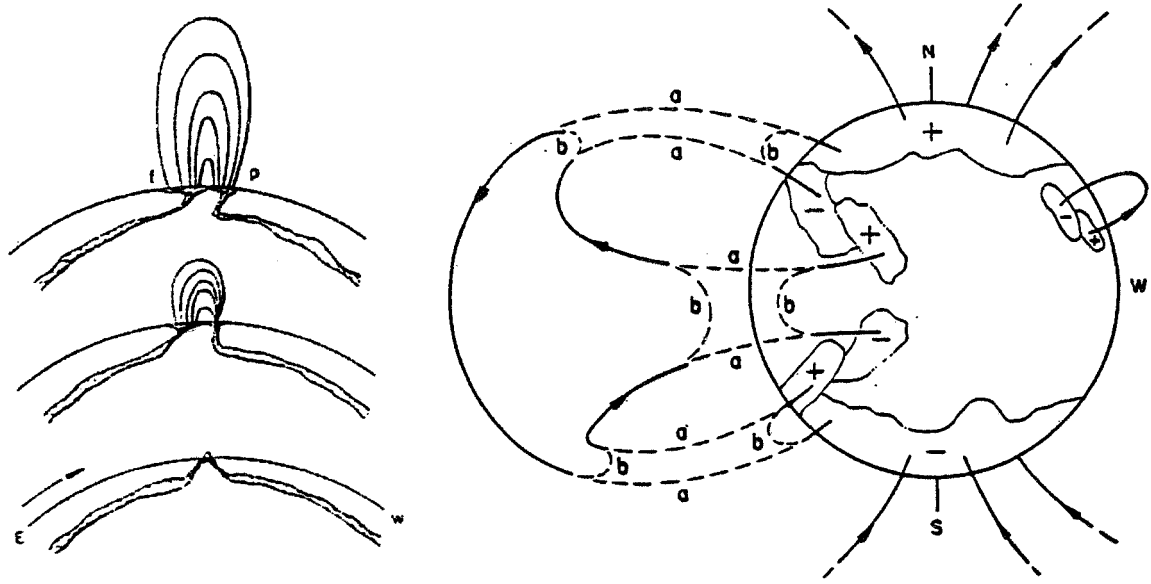


Figure 2: Babcock's Field pictures. On the left is shown how shallow fields in the convection zone erupt to form sunspots. On the right is shown the polar dipole field and the low latitude active region fields (sunspots). The various dashed lines with the letters: a's and b's refer to reconnection of field as the solar cycle progresses. The +'s and -'s refer to field polarities.

Figure 3 shows the overall time history of the Babcock-Leighton picture. This provides a classical, generally well-accepted model for the Sun's dynamo that explains many observed solar features. Unlike a battery-generated dynamo model, where currents flow as the result of differing electron-ion behaviors, in a magneto-hydrodynamic (MHD) dynamo model (which the Babcock-Leighton dynamo is), the medium is regarded as an ideal fluid, with currents and magnetic fields being magnified from pre-existing magnetic fields. It is generally believed the Sun's activity results from such an MHD dynamo. Thus, searching for the source of such fields can lead to understanding the nature of the next solar cycle from the pre-existing detritus field left over from the last cycle. This was essentially inherent in the Babcock-Leighton dynamo, but its usefulness was not employed until a decade later (ref. 5).

In the Babcock-Leighton view an oscillation between the Sun's toroidal field (the East-West fields which erupt to form sunspot fields) and the poloidal field (which extends through the Sun's polar regions) occurs. In summary, the Sun's polar fields near solar minimum are wrapped up by differential rotation to form the toroidal fields (which float to the Sun's surface to form active regions during solar maximum). As these fields then dissipate, they regenerate the polar field, allowing the solar cycle to recur. The remnants of the last cycle thus serve as "seeds" for the next cycle. Modern helioseismological studies have shed new light on the Sun's dynamo; nevertheless, the broad views outlined by Babcock, Leighton, and Hale, et al. (ref. 9) still remain valid.

**Physical basis for solar and  
geomagnetic precursor techniques  
Solar Dynamo**

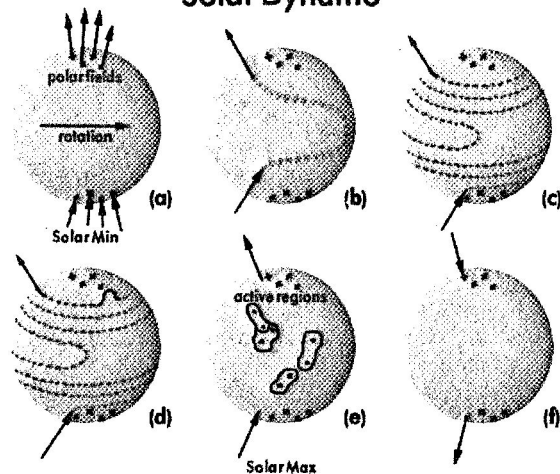


Figure 3: The Babcock-Leighton Dynamo: the Sun's polar fields near solar minimum (a) are wrapped up by differential rotation (b) to form toroidal fields (c). These fields, later in the cycle, float to the Sun's surface and erupt (d) to form active regions containing sunspots (e). The breakup of these active region fields regenerates the Sun's polar field with a reverse sign (f), allowing the process to repeat 11 years later, anti-symmetrically.

The Babcock-Leighton picture provides the key to understanding how to estimate the Sun's buried magnetic flux, and allowing it to be utilized to predict solar activity. The actual solar dynamo is neither as simplified nor "perfect," in terms of perfectly reproducing itself, as suggested by Figure 3, but rather is subject to the vagaries of field magnification within the turbulent convection zone of the Sun. Hence, during an 11-year solar cycle, the amplification sometimes regenerates more polar field and sometimes less, leading to irregular growth and/or decay of the solar cycle. This is well known to solar physicists; as Figure 4 shows, the cycles fluctuate in amplitude. Of particular note are the sharp downturns in activity within a single solar cycle that occurred at the end of the 18<sup>th</sup> and 19<sup>th</sup> centuries.

Let us place the current method of solar activity against the backdrop of other methods, of which there are numerous methods. Here one must try to separate the wheat from the chaff, in a field that can only have a small limited number of "correct" methods, that is overridden with differing methodologies. A decade ago, a NOAA panel (ref. 1) chose the following general solar forecasting categories: Even/Odd Behavior, Spectral, Recent Climatology, Climatology, Neural Networks, and Precursors. "Precursors" were defined to be observations that served as a leading indicator of the size of the upcoming solar cycle. This is similar to how a low pressure in the earth's atmosphere can serve as a precursor to rain. There is a relationship governed by physical laws that can be used as a predictor. The "precursor" category was further divided into solar and geomagnetic precursors. The solar precursor method performed better than the geomagnetic precursors for this last cycle; it is the method we use, and will be the focus of this paper. The solar precursor method exploits some of the physical basis for changing solar activity and the non-random variations. For more information on solar activity prediction methods, including precursor methods, the NOAA panel discussions (ref. 1) provide an excellent source.

In addition to amplitude variations, a Fourier spectrum of solar activity shows "power" in a wide variety of periods beyond the famous 11-year Schwabe periodicity. Additionally, variations exist both on longer and shorter timescales. Further, amplitudes of the cycles vary by more than 100%, in a stochastic manner. Even beyond this, time spans exist, e.g. during the "Maunder minimum" of the 17<sup>th</sup> century (and other similar epochs), during which solar activity dropped precipitously to near zero. The numbering on the chart also illustrates the "Even/Odd" effect, where this past century's (and most of the previous century's) odd numbered cycles have always been larger than the previous even numbered cycle (e.g., cycle #21 > cycle #20, cycle #19 > cycle #18, etc.).

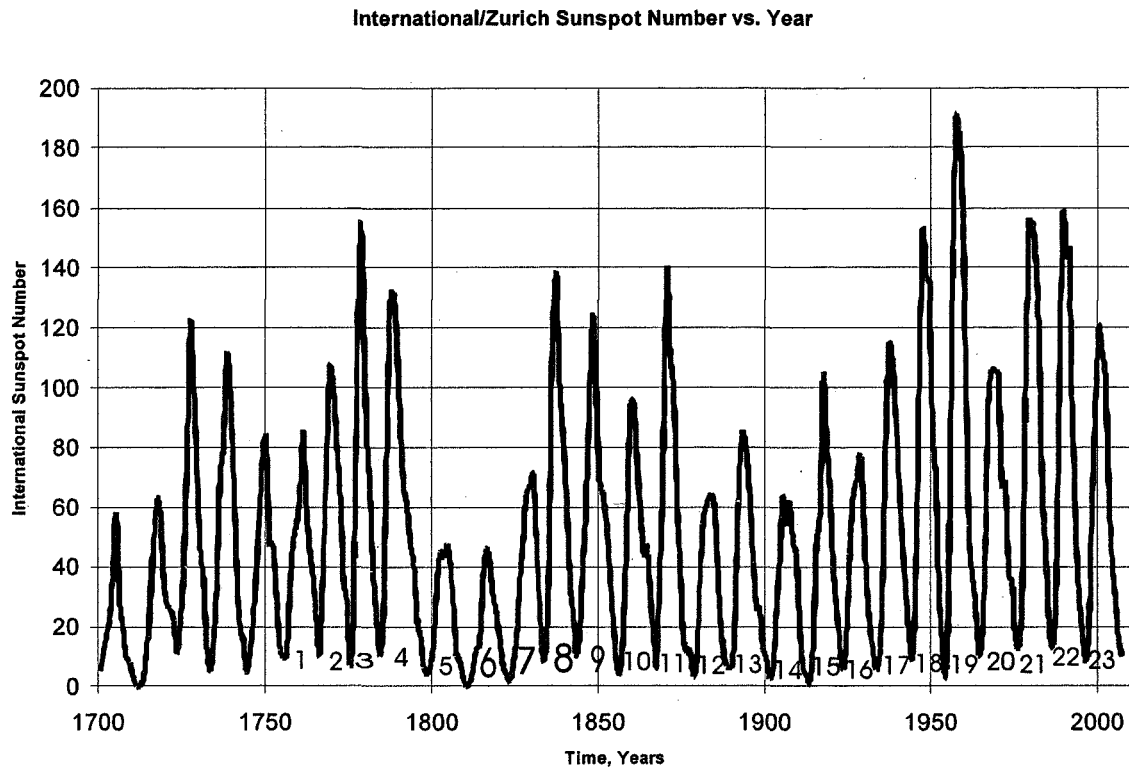


Figure 4: International/Zurich Sunspot Number vs. Time for the Past Few Centuries. The graph also shows the numbered cycles, #1-23, as well as cycles prior to the Schwabe numbering system. As can be seen, variations in basic sunspot number can exceed 100% from cycle to cycle. This does not show the full solar variation, as periods of time prior to this graph exist where sunspot number was much lower than shown here, and much higher as well!

If the Sun's dynamo were fairly linear (as in the Babcock-Leighton model), then one would expect a direct correlation between the number of active regions formed in that cycle with the strength of the Sun's polar field near the cycle's previous solar minimum. In this view, since the polar field of the Sun is later amplified into the sunspot fields, one can use it as a precursor or predictor of solar activity, for that cycle. Namely, by monitoring the observed magnetic fields of the Sun, one can use these observations to predict future levels of solar activity. Similar to the way meteorologists monitor atmospheric pressure regions to predict cloud formation, one only uses current data, and does not rely upon older past data that spectral methods utilize. Hence it is a "physics-based" forecasting technique, which uses recent observations to forecast future solar activity. To validate the dynamo method, 8 solar cycles of historical data were used to test the methods, and reasonable correlations were found (ref. 4). These 8 cycles were not "predictions" since they were not undertaken in advance, nevertheless, this paper made the first prediction using the solar dynamo method. Also actual polar field observations were not available, and only "proxy polar field data" were employed. The method used actual solar magnetic field observations to predict the 3 past solar cycles. We now make a fourth solar cycle prediction for the next decade.

## A PREDICTION FOR SOLAR CYCLE #24

The Solar Dynamo Amplitude (SODA) index provides a continuous measure of the strength of the magnetic field buried within the Sun's interior. Since the magnetic field in the interior of the Sun is "buoyant" (as the magnetic field pressure tends to exclude plasma), the field acts like a gas in a liquid (e.g., carbon dioxide inside a carbonated drink). Hence, the SODA index terminology is not only an acronym, but also a descriptor of the amount of magnetic "fizz" inside the Sun's interior. Figure 5 shows the SODA index in recent times. It has been decreasing during the past decade, suggesting that solar cycle #24 will be smaller than past cycles. Let us also examine the polar field strength levels more directly, and use them for a prediction of the next cycle, to provide some validation.

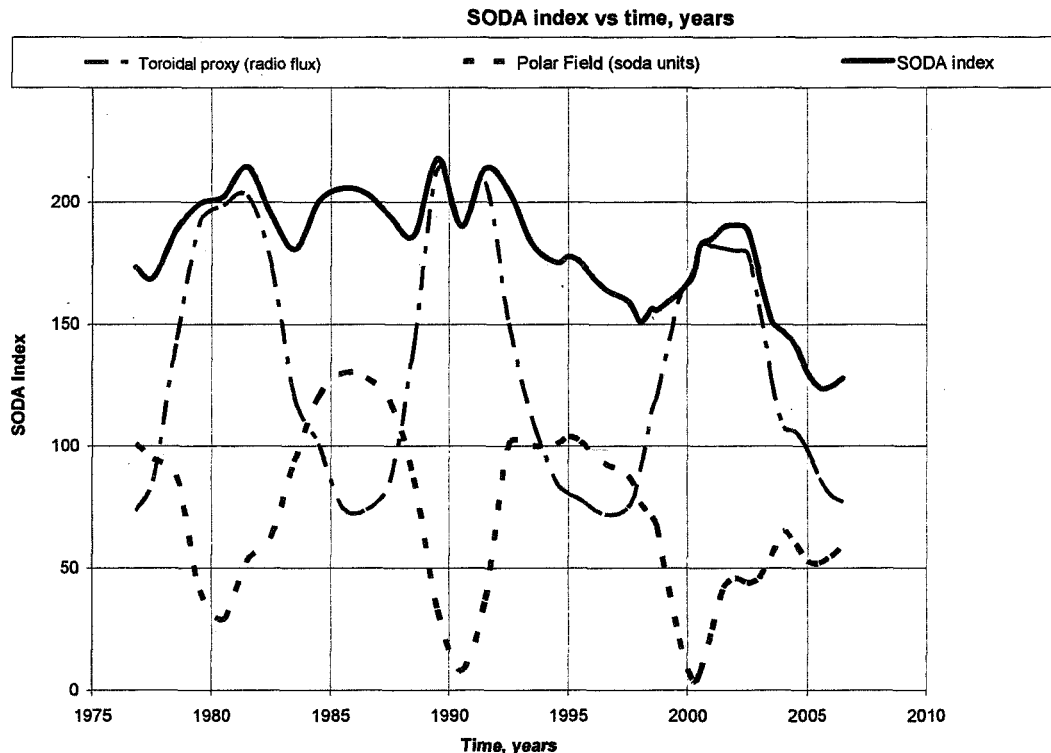


Figure 5. The SODA index is a composite index allowing us to monitor the "buried magnetic flux" present in the Sun's ever-changing dynamo.

At the present time, near solar minimum, the key component is the Sun's polar field. The Sun's polar field reversed near the peak activity of cycle #23 (year 2000), and began its growth toward a new peak with opposite polarity. Figure 6 shows the Wilcox Solar Observatory (WSO) polar field strength measured in the pole-most 3 arc-minute aperture approximately every 10 days (lighter lines), and the smoothed values with a ~500 day low band pass filter (heavier line). During the interval Nov. 2000 and July 2001, the WSO had some equipment problems, and the real fields are likely stronger than those observed; however, this is not near peak polar fields. The Mount Wilson Observatory observations show similar behavior (ref. 10). The Sun's field, being a complex summation of surface features, often described by spherical harmonic components does not show a reversal as neatly as suggested by Figure 5; the north polar field reversed near 2000, and the south field near 2001. After polar field reversal, the smoothed mean polar field rose slowly, and is currently near half the value of that in recent cycles.



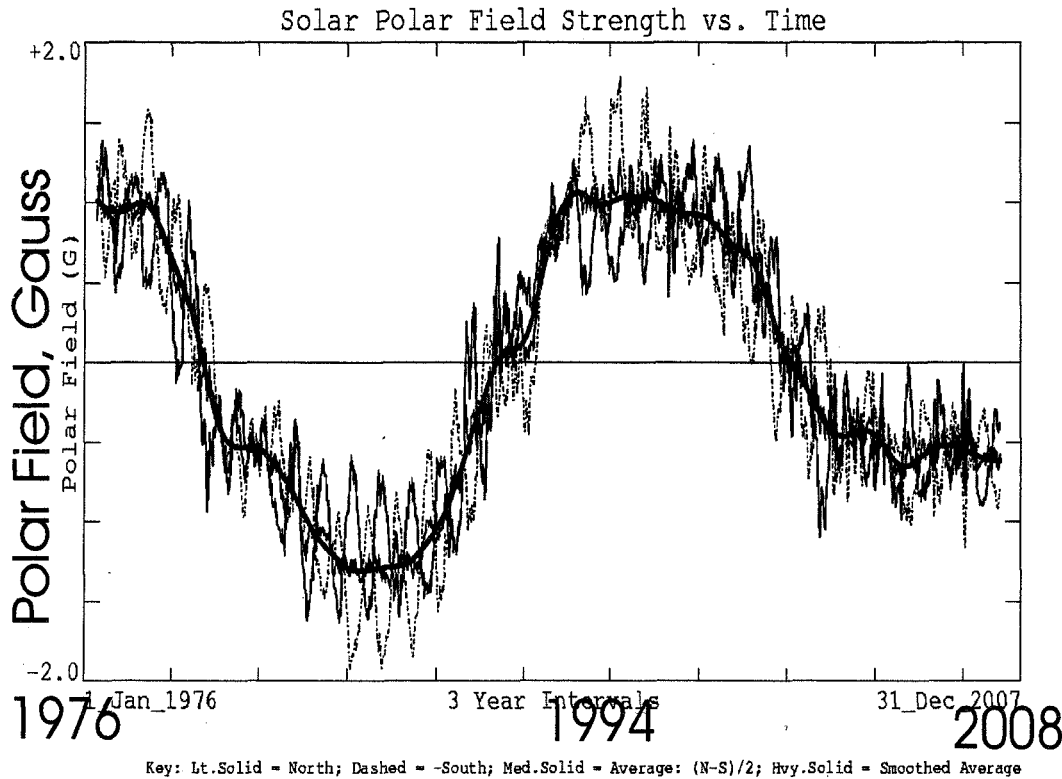


Figure 6: The polar field ( $10^{-6}$  T equal to Gauss) as observed at Wilcox Solar Observatory (WSO). The solid line is the North polar field, and the dashed line, the Southern field. The yearly cycle as the Earth moves  $\pm 7 \frac{1}{4}$  degrees in heliocentric latitude modulates the signal and averages over a year are used as an index. The recent polar field is significantly lower than during the previous 3 solar cycles. The year 1976 is the start of the solar data, and the year 2008 is on the right. Polar fields peak near solar minimum and reverse near solar maximum.

With the current polar field seen in Figure 6 significantly smaller than the peaks of the past three decades, the SODA method (ref. 8) and the polar field precursor method both predict a decreased activity level for the upcoming solar cycle #24. This can be roughly estimated as follows. The SODA (Solar Dynamo Amplitude) index combines polar and toroidal solar fields to create an index, useful for examining the buried solar magnetic flux. Estimated levels are found from field updates of SODA indices. The predicted timing of the cycle has an uncertainty on the order of  $\pm 1$  year. The timing has been based upon the current latitude of active regions ( $\sim$  a few degrees latitude), suggesting the Sun is very near solar minimum. In accord with the SODA index formula provided by Schatten and Pesnell, the current prediction of smoothed Radio Flux, F10.7, for cycle #24 is  $130 \pm 30$  ( $2 \sigma$ ) in the 2013 timeframe, corresponding to a smoothed sunspot number,  $R_z$ , of about  $80 \pm 30$ . The shape of the predicted solar cycle is shown in Figure 7. This Figure and other predictions with these methods, for historical reasons, have been based upon directly Penticton “observed” 10.7 cm solar radio fluxes, as opposed to “adjusted to 1 AU,” or “calibrated”, ie. adjusted to URSI Series D, etc.

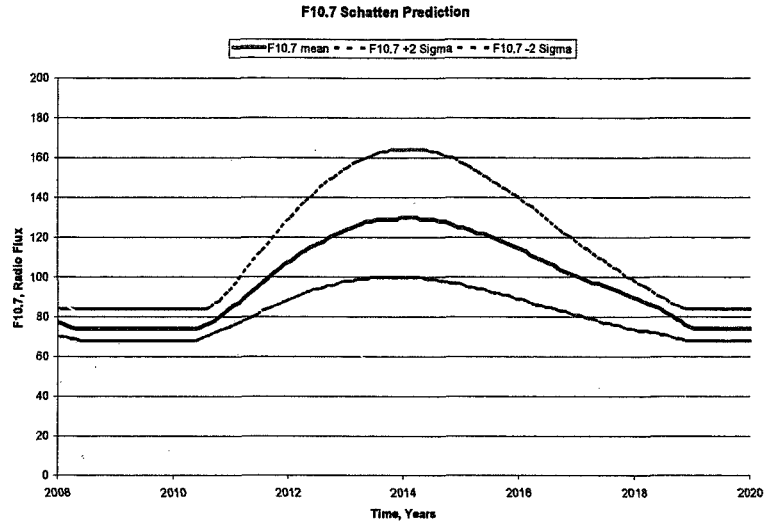


Figure 7: Predicted smoothed Radio Flux (F10.7) is  $130 \pm 30$ , peaking towards the end of 2013. The radio flux is shown from 2008 to 2020 as obtained by the methods outlined here. Units of Radio Flux are  $10^{-22} \text{ J s}^{-1} \text{ m}^{-2} \text{ Hz}^{-1}$ . The  $\pm 2 \sigma$  curves are also provided. Added uncertainties in the timing of  $\pm 1$  year are not shown, but also exist, and are provided to the FDAB (Flight Dynamics).

## OBSERVATIONS RELATED TO POLAR FIELD VALUES

The prediction of reduced levels of solar activity compared to previous cycles occurs primarily from the relatively weak polar fields of the Sun. In addition to the reduced levels of the directly observed fields, there are a number of other relevant observations that support the direct polar field observations. They include an examination of soft X-ray coronal holes, coronal field calculations, and counts of polar faculae. I will only discuss the first observations, although the last two also support the same implications as does the reduced polar field.

An examination of soft X-ray coronal holes was performed to examine what was happening to the Sun's large scale magnetic field. We sought an answer to the question: why and how could the Sun's field dissipate so rapidly? The reduced field patterns seen at the two observatories previously cited suggests that something may have occurred to the structure of the large scale solar magnetic field, different from the normal polar reversal seen in recent cycles. The terms in quotes in the following, refer to the manner in which solar physicists designate aspects such as polarity of active region magnetic fields. In the normal reversal, the field is weakened by "flux injection events" from the "following" polarity magnetic fields of active regions at the sunspot latitudes. These flux injection events in the early phase of a solar cycle reverse the polar field, while later in the cycle they form and magnify "opposite" polarity polar fields.

Once a polar field forms, it is normally readily identified in soft X-ray photos seen from space, where it forms a coronal hole. The reason there is a "hole" in soft X-rays is that the energetic particles flow freely from "open" field lines, and hence, leave them dark. Figure 8a shows a drawing from Harvey and Recely (ref. 11), based upon the He 10830 line. Figure 8b and 8c show X-ray images of the Sun in 2005 and 2007, respectively. In soft X-rays, all the unipolar magnetic regions (UMRs) become evident as coronal holes, similar to the ground-based observations in the He 10830 line. For the present time period (Figure 8c), we see that only quite weak, asymmetric polar coronal holes have formed. This is atypical of coronal holes near solar minimum. The low latitude coronal holes seen in 2005 (Figure 8b) were floating around the solar disk (in longitude) as the Sun rotates with only weak holes located near the safe harbors of the Sun's polar regions. The polar regions of the photosphere can serve as harbors for stable large scale UMRs since only at the poles does differential rotation cease. At other locations (lower latitudes), temporal variations are generally larger due to shear, meridional flow, and active region effects. As a result, low latitude UMRs are subject to continuous change (over months/years). Thus the low latitude 2005 coronal holes, seen in Figure 8b, gradually dissolve by 2007 (Figure 8c). Polar coronal holes usually form a lot sooner in the solar cycle,

and appear to have a larger size, than those seen in Figures 8b and 8c. We note that there are uncertainties in the use of coronal hole data since observing techniques have changed over decadal timescales.

We do not fully understand the reasons for the current reduction in the Sun's polar field. Possible reasons are changes in the Sun's meridional flow or changes in the movement of large scale fields during their reversal phase. For highly conducting plasmas, the magnetic fields are "frozen" to the fluid motions. Thus, flows and field motions are alternative ways of expressing similar views. Additionally, when a strong density boundary occurs (e.g. the photosphere), the fluid motions have a near zero component normal to the surface, and hence the photosphere provides for regions of fluid motion along the surface. This allows for regions of convergence, divergence, and vorticity motions. A solution may be found through understanding the Sun's dynamo as a "surface flow phenomenon," similar to the original Babcock and Leighton viewpoints. Field magnification could occur through surface processes.

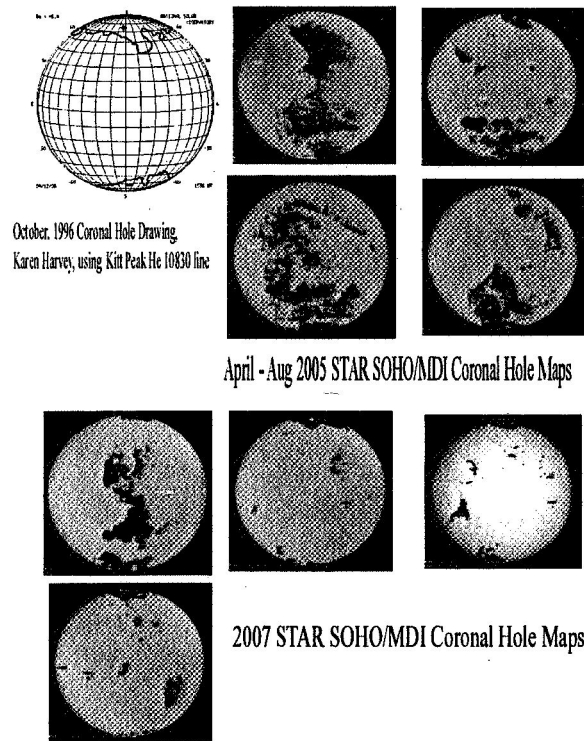


Figure 8. (a -Upper Left) Drawing of coronal holes (seen in He 10830) near the solar minimum of 1996 by Harvey and Recely (ref. 11). Each pole shows a large scale coronal hole, very typical of solar minimum conditions. (b - Upper Right) Shown are a number of views of 2005 coronal hole maps (based on soft X-rays), with four different views over the months between April and August, 2005. (c - Bottom) 2007 Coronal Hole Maps.

## THE SOLAR DYNAMO AS A SHALLOW PERCOLATION PROCESS

On the Sun, there exists small scale magnetic fields in ephemeral active regions (EPRs), recently referred to as the magnetic carpet since they are so numerous their fields form a carpet over the surface of the Sun. We propose that the ephemeral active regions are superficial surface features that grow into larger pores and sunspots, that are well observed, simply due to their convergence. This convergence owes to the dynamics associated with fluid motions in the Sun's upper convection zone that would make "like" magnetic fields stick rather than repel, as is customary in a vacuum. We refer to this process as "percolation," from the latin noun of action, percolare "to strain through, filter," from per- "through" + colare "to strain." We believe the small ephemeral regions and pores are filtered or strained through their motions on the solar surface and thus combine into larger scale entities, forming the active regions, of which sunspots are the most familiar form, and unipolar magnetic regions, of which the Sun's

polar fields are the most obvious example. This suggestion places the origin of the Sun's dynamo field near the photosphere rather than near the base of the Sun's convection zone as most previous dynamo models employ. The photospheric fields may thus simply arise from an accumulation of existing surface fields, which result in the "magnetic carpet" or "ephemeral regions" associated with turbulence, rather than from an erupting flux loop. The gathering together of the small photospheric fluxes in ephemeral regions into larger size pores and sunspots would be aided by the surface fields that Babcock pictures. This would allow sunspot fields to be oriented in accord with Hale's laws of sunspot polarities. More work will be needed to develop these ideas; however, some early understandings are available (ref. 12).

Lest one think that these ideas are totally original or unique, the location of the solar dynamo was originally envisaged as being very shallow by Babcock (ref. 5). Leighton (ref. 6) explored both shallow and deep dynamos. Since their path-breaking analyses, the solar dynamo has predominantly been viewed as deep, owing to there being difficulties in understanding a shallow process in the presence of highly convective overturning. Nevertheless, we have considered rejuvenating this picture in the presence of "percolation", a process we define wherein "like" (same sign) solar magnetic fields stick to each other due to their existence in the superadiabatic environment of the upper convection zone. Figure 9 shows a numerical simulation wherein random bits stick into larger entities.

## Percolation Model

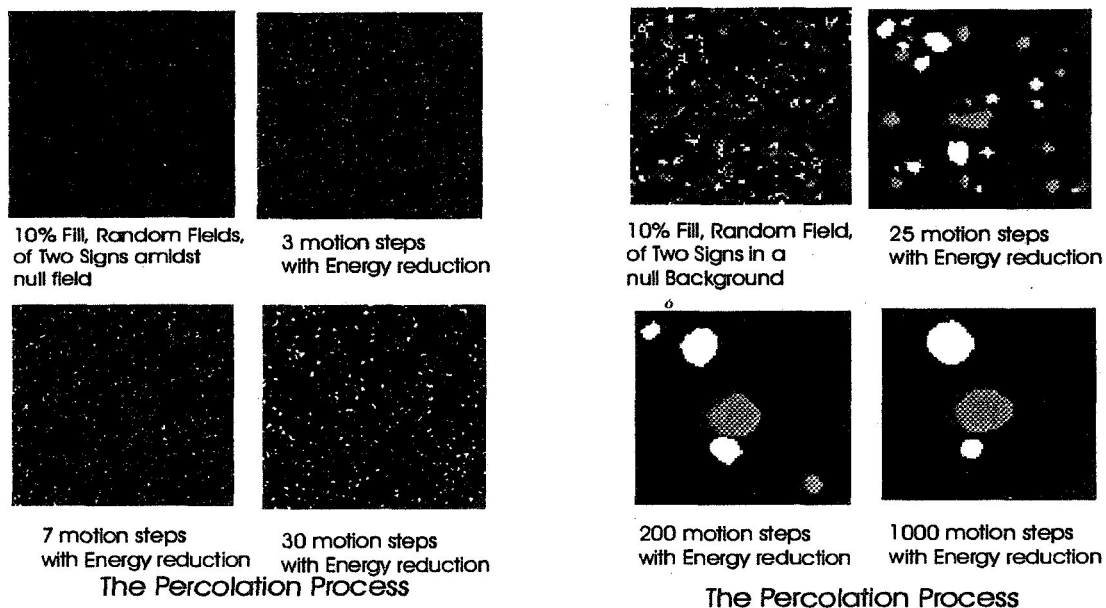


Figure 9. (Left) A cellular automaton model involving many small positive and negative fields with an overall 10% filling factor. (Right) An enhancement of a smaller area showing the growth for a longer duration. Smaller fields eventually combine to form larger entities.

To achieve field "stickiness", the percolation properties we desire for field entities in the photosphere, we use cellular automata with the following properties. The cells exist in a rectangular grid, with toroidal geometry to remove edge effects, by having the left and right edges as well as the top and bottom edges connected. Cells have three states, inward (-), outward (+), and neutral (0). These states are randomly initiated for each cell and do not change. Instead, the cells are allowed to move during each "time interval," until the simulation ends. For each time interval, a number of cell movements may occur through positional cell swapping. When a cell is considered for swapping, the number of same states, in the immediate neighborhood is calculated. If a cell has all the same sign

neighbors, then the cell is internally situated within a pore or spot, and its position is not changed. Otherwise a cell swap may occur based upon probabilities for improved placement. The cells are thus able to generally increase the number of neighbors of same sign cells, resulting in the emergence of clusters of cells in the same state. This essentially provides for an effective clustering, or percolation. Future changes in this methodology may include initiation of field with small dipoles, large scale field interactions with the cells, fluid motions such as differential rotation, and possibly more complex models such as enhanced flows associated with the field geometry and evolution.

In Figure 9 (left side – upper left), a set of ~250,000 cells is chosen in an initial state of 25,000 random bits (of +,-1). This is a 10% filling factor. The zero values are black, the bright values represent + values, and gray areas, negative values. Left side, upper right displays the result after 3 steps; lower left, after 7 steps, and lower right, after 30 steps. Notice that the same percentage (~10%) is filled in each figure, however, the field regions are becoming clustered, due to the percolation or clustering effect. To illustrate the effect of further steps and also examine things on a smaller scale, we see the illustrations on the right side. A smaller scale size, with longer computational steps allows the computer calculations to be performed in reasonable times. Again, upper left is a beginning state. We now choose jumps of 25, 200, and 1000 steps; lower left, after 200 steps, and lower right, after 1000 steps. After 1000 steps, the entire field is in an almost entirely clustered state. Very little happens near the end; the computations only remove two regions, in the last 800 steps.

One other point deserving comment illustrates a lack of agreement between these simulations and observed solar behavior. That is the following. The Sun's magnetic fields not only have a particular individual distribution (small regions of high field strength and large regions of near zero strength), but a large degree of spatial correlation, or spatial coherence. The former relates to filling factor and this we purposely overestimated for illustrative purposes. The latter relates to how the fields are distributed into active regions, which generally have fields of both signs (bipolar magnetic regions), thus the presence of a large positive (sunspot) field is often correlated spatially with negative fields (opposite sign sunspots) nearby. Our simulations do not show this. We suppose that our simulations are missing something, but our mechanism (of field percolation) could also be incorrect, and the upwelling of flux loops adequately explains this well-known fact of solar behavior. Our percolation model is highly simplified; it starts with random unipolar fields. Thus there are two independent distributions of unipolar fields which evolve independently, except they cannot both occupy the same space, rather than starting as close bipolar pairs as ephemeral regions do, owing to Maxwell's divergence B equation. Thus our model is simplified, compared with the Sun, by not having highly correlated small bipoles (EPRs), and other aspects that treat percolation in a simplified fashion, rather than how real flows on the Sun could draw actual field structures together.

## SUMMARY AND CONCLUSIONS

This paper outlines the polar field precursor method for solar activity forecasting. The polar field observations suggest a peak (smoothed) activity level for solar cycle #24 of about  $130 \pm 30$  ( $2 \sigma$ ) for F10.7 Radio Flux and  $80 \pm 30$  ( $2 \sigma$ ) for sunspot number. Support for reduced polar fields is found from the apparent reduced size of coronal holes. Nevertheless, we note that coronal hole data must be further examined as observing techniques have changed over long timescales. In addition to an apparent reduction in their apparent size, their behavior appears to be quite different in morphology. There have been many examples of these fields drifting at low latitudes during the late phase of cycle #23. This is quite unusual. Normally they are at the poles during the late phases. This suggests that much of the Sun's polar fields have "disappeared" by reconnection at low latitudes, where they can then escape into the solar wind. As a consequence, cycle #24 may not have a "full load" of explosive magnetic field to rearm itself with. We are in awe of being able to see an object the size of the Sun undergoing as dramatic a change as this in a few short years. Since the Kelvin-Helmholtz timescale for the Sun is about 20 million years, people have naively taken the Sun to be constant. Modern observations show dramatic changes in very short timescales belying steady-state theories. The weather on the Sun is at least as fickle as the weather on the Earth. Concomitant effects of low solar activity upon satellites in LEO will need to be considered by NASA, such as enhancements in orbital debris.

Shallow dynamo models of Babcock and Leighton have often been utilized with a deep origin for the Sun's dynamo fields. This places source of the field near or below the base of the Sun's convection zone. In contrast, we suggest that magnetic fields in the photosphere may simply arise from an accumulation of existing surface fields rather than from an erupting flux loop. The gathering together of the small photospheric fluxes in ephemeral regions into larger size pores and sunspots would be aided by the surface fields that Babcock pictures. This would allow sunspot fields

to be oriented in accord with Hale's laws of sunspot polarities (ref. 9). A percolation process with a cellular automaton model appears to be able to mimic some solar features. More work in this area is planned.

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